SPECIAL CONTRIBUTIONS.

ANEMOMETER TESTS.

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The present paper aims to give briefly the results of a limited series of experiments recently conducted by the writer to determine the law of action of a small anemometer employed on kites to record the motion of the wind in the free air. For the benefit of those readers of the REVIEW who may not be familiar with experimental work of this character the general question of anemometer testing is also very briefly discussed.

INTRODUCTION.

Methods of testing.—When we employ a given instrument to measure the motion of the wind, the instrument is set up in a fixed position while the wind blows past it. If now we could, independently, ascertain satisfactorily the velocity of the wind during any given interval, it would be an easy matter, from suitable observations under such circumstances to determine the law by which to convert the readings of the instrument into the speed of the wind. Such a method of testing anemometers, however, is not broadly available (1), because we have no means of accurately measuring the speed of the wind, except by some other anemometer which must itself be first tested, and (2), because such experiments do not conveniently afford the range of velocities ordinarily desired. Experiments of this kind are, in fact, simply comparisons between one or more instruments.

In the face of these difficulties those who have sought to solve this problem have been led to adopt the expedient of moving the instrument to be tested at the desired velocity through comparatively still air. In these cases it is assumed that the moving anemometer in still air will behave like the stationary anemometer in moving air. In the older experiments made by this method the instrument was placed on the free end of a horizontal arm arranged to revolve on a vertical axis. The anemometer could thus be made to pass in a circular path through relatively still air.

Various difficulties developed in carrying out experiments by this method all more or less directly due to confining the motion of the anemometer to a circular path of comparatively small diameter. When this was recognized some efforts were made to standardize particular types of anemometers under conditions of straight-line motion such as afforded on locomotives or specially prepared cars running at various speeds across the open country. While this obviates the difficulties of curvilinear motion others of greater consequence are introduced; for example, it appears quite probable that the excessive vibration characteristic of railway trains in rapid motion has an appreciable effect on the friction of most forms of anemometers. Moreover, the difficulty of making due allowance for the natural wind that may be blowing at the time is a very serious one so that results by this method have thus far scarcely equaled in accuracy those otherwise obtained.

In 1888 the writer undertook a series of tests of the standard anemometers employed to measure wind velocity at Weather Bureau stations, and, for this purpose, designed a whirling machine of unusually large dimensions. The maximum length of the arm was 35 feet, measured from the center of the vertical axis to the anemometer axis. At that time it was aimed to conduct the tests in perfectly still air, as nearly as could be obtained, and to this end experiments were made at nighttime in the great closed court of the Pension Building which afforded ample space for the whirler, large as it was. An extensive series of experiments was carried out under these conditions of steady, uniform, motion over a circular path of large diameter. and through practically still air. Anemometers of various dimensions, as well as the standard type, were tested with closely concordant results. When, however, these instruments were afterwards compared in the open air, systematic differences immediately developed, and it was soon discovered that a new factor, not previously considered, must be recognized in conducting anemometer tests; namely, that owing to the inertia of the revolving parts of the ordinary instrument a steady wind will cause it to give a different indication than will result in a gusty wind of the same average velocity. (The word gusty is used throughout this paper to mean—*characterized by marked, sudden, and irregular changes of velocity.*) All natural winds, as far as they have ever been analyzed, prove to be extremely variable, that is, gusty. This being the case it was therefore, a mistake to aim to secure perfectly steady motion in still air during the whirling machine experiments, since, as the instruments were intended for use in the gusty, open-air winds, the artificial test winds should also have been gusty to a corresponding degree. The whirling machine having been necessarily dismantled before the above stated principle was brought out, further experiments in this direction could not be made, but the results of the tests of the standard Weather Bureau anemometer were reduced to open air conditions; that is, to gusty winds, by means of comparisons with small anemometers of slight inertia.[1]

Best conditions for whirling machine experiments.— As a secondary result of the researches referred to, it has long been the writer's opinion that, with proper precautions anemometer tests are best made by the use of a large whirling machine, freely exposed in the open air. The experiments should be made while there is more or less natural wind blowing. It is only necessary to seek a free and open exposure so as to avoid local and abnormal peculiarities in the natural wind, and to deal with a large number of experiments so as to eliminate the large accidental irregularities. The presence of the natural wind has the effect of alternately adding to and subtracting from the artificial wind resulting from the steady motion of the whirler, so that the actual resultant wind affecting the anemometer thereby acquires a gusty character with a maximum and minimum velocity once in each complete turn of the whirler. This resultant velocity is made still further irregular by the variations in the natural wind. The artificial, gusty wind thus secured affords a highly appropriate test wind for anemometers that are to be used in the open air.

RECENT EXPERIMENTS.

It became necessary recently to test a small form of anemometer used on kites, and, guided by the considerations stated above, the large whirling machine formerly used was rehabilitated during May, 1899, and installed at Arlington, Va., adjacent to the automatic steam kite reel, a location which afforded an exceptionally free exposure in the open air.

The whirling machine.—The construction of the machine is readily understood from fig. 1, Pl. I. The slender horizontal arm was made up of sections of standard wrought-iron pipe, of which the central piece was 2½ inches nominal inside diameter. The distance from the central axis to the axis of the anemometer was 28.01 feet (8.54 m.). In the early experiments, made in 1888, it was demonstrated that this length was ample to eliminate the more serious defects of circular motion, and it was adopted because it leads to a very simple and convenient mathematical relation employed in computing the velocity at the end of the arm. The equations will be given further on. Originally the whirler was

[1] Annual Report of Chief Signal Officer, 1890, p. 691.

driven entirely by hand power, but in the present case a long rope-belt connection was made with the small steam engine employed to run the automatic kite reel. Thirty-five miles per hour was about the highest speed that could be given the anemometer by hand power. With the small steam engine a velocity at the end of the arm of nearly 60 miles per hour could be maintained.

The arrangement of the apparatus is shown in fig. 1, Pl. I. The anemometer on the end of the arm is one of the small type used on kites. Two other anemometers are seen in the picture. These represent two methods that were employed to measure the natural wind movement during an experiment. In the earlier tests this wind movement was deduced from the record made by an anemometer surmounting the central axis of the whirler. Since in this case the whole anemometer revolves with the fixed central axis of the whirler, it is plain that when the anemometer cups and whirler revolve in the same direction the speed of the wind must be deduced from the *sum* of the turns of the whirler and the recorded rotations of the cups, but from the *difference* of these when the directions of rotation are opposed to each other. A difficulty developed here when there was little or no natural wind and the speed of the whirler was considerable. This will be understood from what follows. The central anemometer recorded by momentarily breaking the electric circuit, generally once for each revolution of the cups. If now the whirler and anemometer revolve in the same direction and at the same speed, no record should be made, but if it so happens that the motion of the cups is in the act of causing a break in the circuit, it is easy to see that natural variations in the wind will cause the cups at one moment to go a little faster than the wind and at the next to slow up and lag behind the whirler in speed, thereby causing, perhaps, several electrical records to appear where but one or none should be found. Even if there is no apparent defect of this sort in the record, there is yet the possibility that at times some of the recorded breaks of the circuit should be counted up in the negative sense.

The central position was regarded as the best for the anemometer employed to measure the natural wind, but it had, nevertheless, to be abandoned for the reasons given above, and an anemometer seen at the left of fig. 1, Pl. I, was used instead. Generally, this was directly to windward of the axis of the whirler.

Ordinarily, the machine was driven by the steam engine. In a small number of tests at very slow speeds, however, the whirler was driven by hand, either by use of the crank, plainly seen in the picture, or by use of the annular wooden ring also seen leaning against the framework of the machine. When this is used the small horizontal countershaft is removed and the annular plate bolted securely down upon the large gear on the central shaft. The operator then takes up a convenient position and drives the machine at the desired speed by force applied to the handles projecting above the plate. This mode of driving the arm yielded exceedingly smooth, steady motion, and is the one employed in the early experiments of 1888.

Anemometers.—Fig. 2, Pl. I, shows the kite anemometer as attached to a spar on the kite. The clamp admits of adjusting the axis to an approximately vertical position according to the average angle of incidence of the kite. The pins on the dial wheel *close* the electric circuit after 3,000 revolutions of the cups. A special contact was used during the experiments which operated to *break* the circuit momentarily each 500 turns of the cups. Two similar anemometers of this small size, designated kite No. 1 and No. 2, respectively, were tested. The latter, however, received only two tests. In addition, a number of tests were made of a standard aluminum cup anemometer, such as used at stations. Tests were likewise made of two sets of paper cups.[2] These were of the same dimensions as the aluminum cups, but of extremely light construction. Owing to their frailty the tests were limited to low velocities. Their extreme lightness rendered them especially responsive to marked and sudden variations of the wind velocity, and, for this reason, they were principally used in the measurement of the natural wind. In this case electrical registration during light winds was effected for *each rotation* of the cups and for each ten revolutions in stronger winds. When the aluminum or paper cups were tested on the whirler a special spindle[3] was employed which produced a momentary *break* in the electric circuit for each 100 revolutions of the cups. This spindle was provided at the top with the rolling bearings, shown in fig. 3, that afforded the minimum frictional resistance. In the early experiments in the Pension Building court it was shown that the diminution of friction resulting from the use of this bearing led to only a slight influence on the indications of the instrument. In other words, the standard Weather Bureau anemometer is of such excellent construction that the friction exerts a barely appreciable influence on the running of the instrument. It may be noted in this connection that the friction in an anemometer undergoing test on a whirling machine is greater than in the ordinary use of the instrument because of the centrifugal action in the curvilinear path. On this account it is judged to be preferable to use the rolling bearings in whirling machine tests, especially when the length of the arm is only 10 or 15 feet and less, as in most of the experiments prior to those conducted by the writer.

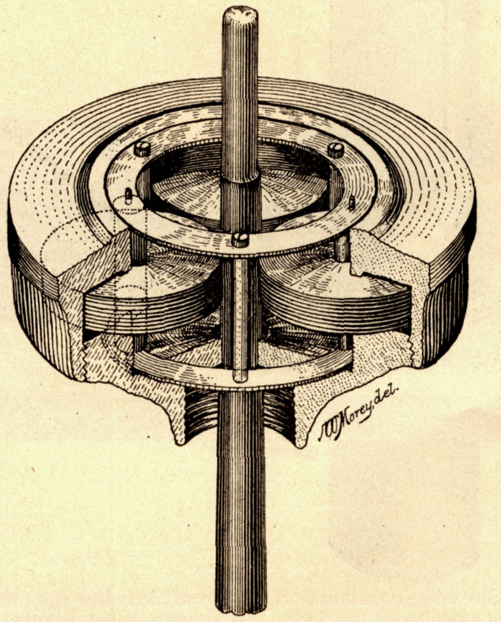

FIG. 3.

Automatic registration.—The conditions of the experiments require: (1) Record of the revolutions of the anemometer

[2] All the standard anemometers of the Weather Bureau are made in two separate parts, which are all perfectly interchangeable. It is customary to call these parts, respectively, "the cups," or "set of cups," and "the spindle," or sometimes the "anemometer without cups." A "set of cups" consists of four hemispherical cups mounted on steel cross arms provided with a suitable hub at the center which latter is bored to fit the steel rod forming the axis of revolution of the anemometer. In all cases the cups are so mounted as to revolve clockwise; that is, a cup moves from the north around to the east, south and west.

[3] The spindle comprises the remaining parts of the instrument consisting of the steel axis with all its mountings, worm, gearing, dials, and electrical devices employed to measure and indicate the revolutions of the cups. These words will be used in this sense of this paper.

undergoing test; (2) a record of the turns of the whirler during the same interval; finally, (3) a record of the revolutions of the anemometer employed in measuring the natural wind. In addition, we need to be able to determine easily the speed of the whirler at any moment and to regulate the same as may be desired.

For these purposes a good break-circuit, seconds pendulum clock was employed, together with the Alvan Clark astronomical chronograph, provided with two recording pen carriages. The clock and chronograph with necessary batteries were installed in a suitable shed about 150 feet south of the whirler. Electrical connections were made by means of a three-conductor cable buried just below the surface of the ground. One of the wires of the cable made direct metallic connection with the whirler, the shed end of the same wire being joined to similar poles of two batteries. The opposite pole of one of these batteries was connected by wire to the clock, thence to No. 1 carriage on the chronograph; thence, to an ordinary telegraph sounder located near the engine; thence, to a break-circuit spring operated by the whirler, see fig. 4; thence, along the arm to the anemometer on the end, where metallic connection was again made to the whirler.

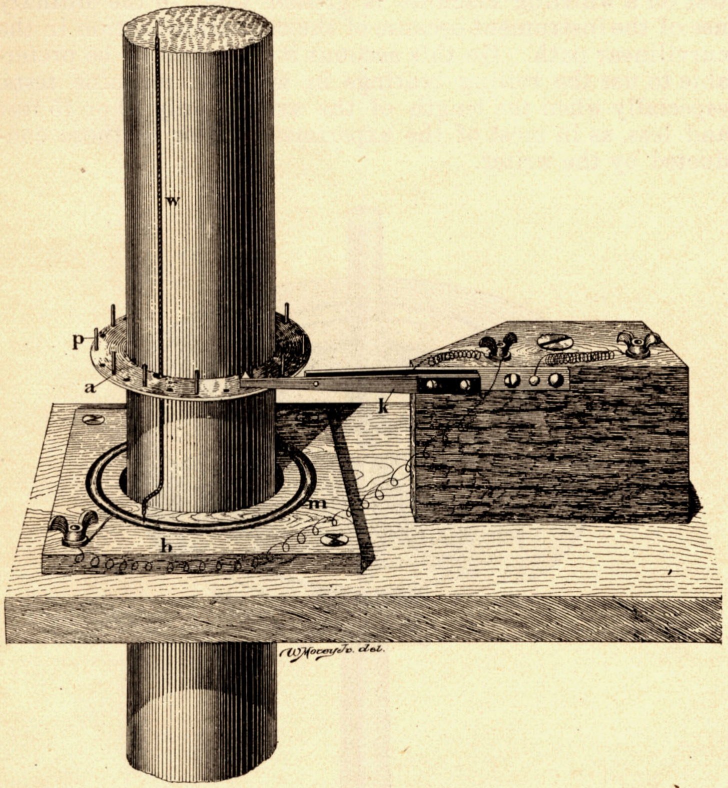

FIG. 4.—Showing construction of circuit breaker operated by whirling arm, as employed in 1888. In recent experiments the annular mercury trough, *m*, through which electrical connection was made with the wire *W*, was replaced by a brush contact on an insulated ring on the shaft.

The free pole of the second battery was connected direct to the No. 2 carriage on the chronograph; thence to the anemometer employed to measure the natural wind. When this instrument was erected on the pole a connecting wire joined the circuit to the main battery wire in the cable. Both systems were on closed circuits.

The chronographic record produced by the No. 1 carriage embraced (*a*), the regular beats of the seconds pendulum; (*b*), the frequent beats marking the revolutions of the whirler; (*c*), the infrequent breaks in groups of 100 or 500 turns, as the case might be, marking the revolutions of the anemometer to be tested. In the meantime the No. 2 carriage produced its records of the rotations of the anemometer employed to measure the natural wind. In light winds every revolution of the cups was recorded. Generally, each break of the circuit represented 10 turns of the cups.

Prior to starting a record it was customery to cause the two pens of the chronograph to make marks on the record sheet while the cylinder was stationary. From marks thus made simultaneous times could afterwards be laid off on the two records with extreme accuracy.

The telegraphic sounder located near the steam engine or whirler gave an audible effect corresponding to the several events recorded by the No. 1 pen carriage and enabled the operator to judge of the proper action of the whole apparatus and to regulate the speed of the whirler as might be desired. This was further facilitated by the convenient mathematical relation resulting from the use of a 28-foot arm which gives rise to the following equation for the velocity at the end of the arm:

$$V = 120 \frac{N}{t} \text{ in miles per hour.}$$

N is the number of revolutions of the whirler in t seconds. The axis of the whirler carries an annular disk, pierced with 24 equidistant holes, to which are fitted 24 removable pins. As the axis revolves, the pins that may be inserted in the holes break the electric circuit. If now 24 pins are in position and the speed is regulated so that the electric circuit is broken every two seconds, we will have a speed of one revolution in forty-eight seconds; that is, 2.5 miles per hour at the end of the arm. If every other pin is removed, that is, if the disk contains 12 equidistant pins, and the arm is speeded until a break is again made every two seconds, we get a velocity of 5 miles per hour. Six pins give 10 miles an hour; 4 pins, 15 miles an hour; 3 pins, 20; 2 pins, 30, and 1 pin, 60 miles per hour. With a little practice it is easy for the operator, guided by the telegraph sounder, to regulate the speed with great exactness, especially in quiet air and with moderate speeds. When using the steam engine it was customary to place only one pin in the disk. For 30 miles an hour the engine was speeded to give a break every four seconds; every three seconds resulted in 40 miles per hour, etc. Variations in the velocity of the natural wind had a noticeable effect on the speed of the whirler while driven with a fixed expenditure of power.

Reduction to rectilinear motion.—A test of an anemometer of the Robinson type at a given velocity is not complete unless a result is obtained when the whirler is revolved in both the forward and backward sense. When the whirler turns in the north, east, south, west direction, the anemometer cups revolve in the same sense, and the driving pressure of the wind acts upon the concave cups while they are nearest the central axis of the whirler, in which position the artificial wind velocity is less than that of the opposing wind acting upon the concave cups which are then in a position farthest from the axis. Under these conditions the anemometer will run at a slower rate than if its axis moved at the same velocity along a rectilinear instead of a curved path. On the other hand when the whirler revolves in the north, west, south, east direction the conditions are reversed and the anemometer runs faster than for rectilinear motion.

If the length of the anemometer arms is small, relative to that of the whirler, the mean of the results for right and left-handed motion is equivalent to a result for rectilinear motion.

In this connection we need to observe that the number of revolutions of the cups registered by the counting mechanism after a given interval, is not the actual number of turns, but only the number in relation to the whirling arm, which itself may in the meantime have made several revolutions. To find the real number of turns of the anemometer cups during any time it is necessary to add or subtract from the apparent number one turn for each revolution made by the whirling arm. A knowledge of this fact has led some to suppose that such a correction should be applied to all whirling machine experiments, but such is not the case, for the reason that while such a method would give the actual number of revolutions of the anemometer cups in relation to any fixed object, yet, since the direction in which the air acts upon the cups of the anemometer is itself as the arm revolves, continually changing, relative to the fixed object, it follows that the real number of turns of the cups in relation to the air which makes them revolve is, after all, simply the apparent number of turns indicated by the dials. It is, therefore, erroneous to apply any correction of this kind as one is at first led to suppose.

Correction for natural wind. It is sometimes hastily concluded that a natural wind acting uniformly throughout the whole orbit of the whirler neither adds to nor detracts from the movement of the anemometer being tested, because the loss in one-half the orbit is made up by the gain in the other half. This is a mistake, and it can easily be shown that there is an appreciable gain in all cases. The magnitude of the momentary resultant wind, R, is shown graphically in fig. 5 for several positions of the anemometer.

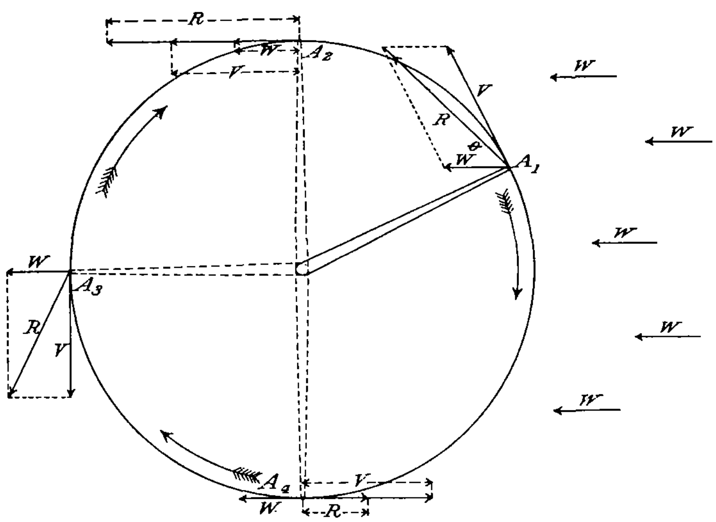

FIG. 5.—Diagram of resultant wind R for anemometer moving at speed V and influenced by a uniform natural wind at velocity W.

The mean resultant wind for the whole orbit may be found graphically by the aid of a diagram like fig. 6. The semicircle is struck with a radius V representing the speed of the anemometer, and subdivided into a convenient number of sectors, as indicated. The resultant R is found for each point; and the sum of these for the entire orbit divided by the number of points taken gives the mean resultant wind that should be used in reducing the observations. The writer has employed this graphic method of deriving the resultant wind in a few cases largely as a check on results deduced numerically by the use of the following equation:

$$R = V + \frac{W^2}{4V} + \text{etc.} \tag{1}$$

which is obtained by the methods of calculus from the equation:

$$R = \sqrt{V^2 + W^2 + 2VW\cos\theta}$$

giving the value of the resultant at a point where θ is the angle between the two motions V and W.

The first two terms of equation (1) are ample for all ordinary cases.

Table 1, deduced from an actual test, gives the momentary value of the resultant at successive points in the rotation of the whirler during a strong wind, and illustrates the very gusty character of the resultant wind acting upon the anemometer.

TABLE 1.—*Momentary resultants at 32 points of orbit.*

Velocity of end of arm: V=37.11 miles per hour. Mean velocity of natural wind: W=17.52 miles per hour.

Point.	Resultant.	Point.	Resultant.	Point.	Resultant.	Point.	Resultant.
1	54.63	9	41.10	17	19.59	25	41.10
2	54.38	10	37.90	18	20.19	26	44.07
3	53.70	11	34.51	19	21.85	27	46.70
4	52.57	12	31.08	20	24.62	28	49.15
5	51.02	13	27.75	21	27.75	29	51.02
6	49.15	14	24.62	22	31.08	30	52.57
7	46.70	15	21.85	23	34.51	31	53.70
8	44.07	16	20.19	24	37.90	32	54.38
Mean..	....	....	....	....	....	....	39.23

Mean resultant deduced by equation (1) $R = 39.18$.
Mean resultant deduced by graphic method, 39.23.

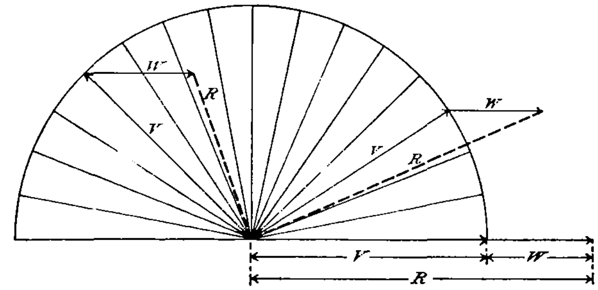

FIG. 6.

At the speed in question the whirler was turning at the rate of one revolution in 3.3 seconds, and in each rotation the resultant speed varied from 19.6 to 54.6 miles per hour. These were extreme conditions, but the result obtained corresponds satisfactorily with others under average conditions.

Experiments described.—In conducting a test an assistant starts the chronographic record while the whirler is brought to the desired speed, which is then maintained as steady as practicable for a period of from five to ten minutes, according to circumstances. Thereafter other tests are made at different speeds. As far as possible the tests were arranged in pairs, embracing both right-handed (N. E. S. W.) and left-handed (N. W. S. E.) directions of rotation of the whirler. The change in direction was effected by crossing the rope driving belt.

The chronographic record traced by the No. 1 recording pen, gave the following data: (a), The elapsed time, in seconds and tenths, of each group of registered rotations of the anemometer being tested; (b), the number of revolutions made by the whirler in this same time. Finally, by projecting the simultaneous time upon the record of the natural wind as traced by the recording pen No. 2, the number of revolutions made by this anemometer in the same interval of time could also be ascertained with accuracy. A simple inspection of the whirler marks on the chronographic record enabled one to judge accurately of the speed of the arm and the regularity of its motion. In computing results it was customary to tabulate the elapsed time for each registration of the anemometer. The uniformity in these times was a fair evidence of a satisfactory set of conditions. The sum of these times, that is the total time from the first to the last registration of the anemometer, represented the real duration of the test and is given in the column headed t, in Table 2, which gives in chronological sequence the data for all the tests.

TABLE 2.—*Anemometer tests on whirling machine in open air.*

Date.	No. of experiment.	t.	u.	N.	R.	W.	Instrument.	Direction.	U.
1899.									
May 18[1]	1	378.8	3,500	63.0	21.50	10.9	Kite No. 1	Right	1,547
Do.	2	383.3	3,500	64.0	20.99	8.9	do.	Left	1,566
Do.	3	277.0	2,500	46.0	20.78	7.9	do.	Right	1,564
Do.	4	259.9	2,500	43.3	21.56	11.15	do.	Left	1,606
May 19	5	846.0	14,500	261.6	39.18	17.52	do.	Right	1,575
Do.	6	258.0	1,500	72.5	35.39	......	Aluminum	do.	591
		467.5	3,000	145.0	38.73	......	do.	do.	596
		755.6	5,000	245.5	40.43	......	do.	do.	589
Do.	7	575.5	4,300	195.3	42.10	......	do.	Left	639
May 20	8	527.6	10,000	183.6	42.93	13.99	Kite No. 1	Right	1,589
Do.	9	509.7	9,500	171.6	40.98	9.66	do.	Left	1,637
May 22	10	382.0	300	16.1	5.75	3.73	Paper No. 1	Right	492
Do.	11	382.9	300	16.1	5.38	2.56	do.	Left	524
Do.	12	406.3	300	17.8	5.55	2.98	Paper No. 2	Right	479
Do.	13	500.9	400	20.7	5.38	2.88	do.	Left	534
May 23	14	450.6	8,500	162.2	43.44	6.38	Kite No. 1	Right	1,563
Do.	15	443.8	8,500	158.3	42.97	5.36	do.	Left	1,605
Do.	16	436.7	8,000	145.5	40.31	7.22	Aluminum	do.	614
Do.	17	307.3	2,000	105.2	41.47	8.00	do.	Right	565
Do.	18	314.8	2,000	101.5	39.35	10.14	do.	do.	581
		68.8	500	25.3	44.56	8.72	do.	do.	587
May 26[2]	19	193.9	3,000	58.1	36.17	5.47	Kite No. 1	do.	1,540
		220.5	3,000	58.0	31.60	2.13	do.	do.	1,550
Do.	20	184.5	4,000	74.2	48.40	5.13	do.	Left	1,613
		179.0	3,000	56.0	37.79	6.13	do.	do.	1,597
May 27	21	277.5	5,500	105.8	45.85	4.32	do.	Right	1,556
		129.8	3,000	57.0	52.81	4.91	do.	do.	1,576
Do.	22	289.3	5,500	105.2	43.80	5.33	do.	do.	1,563
Do.	23	199.1	4,000	74.6	45.12	5.43	do.	Left	1,603
		85.3	2,000	36.7	51.75	4.98	do.	do.	1,631
Do.	24	371.0	2,000	31.0	11.48	7.63	do.	Right	1,691
		284.9	1,500	23.8	11.37	7.35	do.	do.	1,667
Do.	25	298.8	1,500	25.0	11.11	6.55	do.	Left	1,627
May 29	26	355.1	600	29.9	11.46	7.40	Paper No. 2	Right	531
Do.	27	447.7	800	37.6	10.93	5.86	do.	Left	588
Do.	28	334.3	600	27.9	11.16	6.78	Aluminum	Right	579
Do.	29	406.8	800	33.7	11.21	7.11	do.	Left	632
Do.	30	334.0	600	28.7	11.58	7.37	Paper No. 1	Right	558
Do.	31	212.7	400	17.7	11.31	7.18	do.	Left	599
June 3	32	336.9	1,500	28.1	10.59	4.83	Kite No. 1	Right	1,514
Do.	33	224.7	1,000	18.7	10.58	4.87	do.	Left	1,514
		93.8	500	7.8	11.12	6.74	do.	do.	1,726
Do.	34	314.2	4,500	85.0	32.97	8.16	do.	Right	1,564
Do.	35	330.5	1,600	85.5	31.36	6.31	Al. cups.	do.	556
Do.	36	280.9	1,300	69.9	30.22	6.54	do.	do.	551
Do.	37	557.4	3,100	152.9	33.27	6.76	do.	Left	602
Do.	38	389.5	5,500	100.3	31.48	8.43	Kite No. 1	do.	1,600
Do.	39	561.0	9,000	165.4	35.89	8.47	do.	do.	1,609
Do.	40	340.7	7,000	129.6	45.96	7.56	do.	do.	1,609
Do.	41	620.9	12,000	227.4	44.33	8.14	do.	Right	1,570
Do.	42	619.4	4,000	209.3	40.84	6.87	Al. cups	do.	569
Do.	43	314.7	1,900	102.2	39.12	4.78	do.	do.	556
Do.	44	288.7	4,500	86.9	36.28	4.79	Kite No. 1	do.	1,547
Do.	45	55.0	1,000	19.2	42.12	6.24	do.	do.	1,554
June 13[3]	46	373.8	850	16.0	5.60	3.07	Kite No. 2	do.	1,462
Do.[3]	47	372.6	800	15.5	5.18	1.85	do.	Left	1,492
Do.[3]	48	320.9	200	13.4	5.22	2.05	Paper No. 2	Right	430
Do.[3]	49	384.7	300	16.5	5.63	3.15	do.	Left	499
Do.[3]	50	290.2	200	12.5	5.49	2.57	Paper No. 1	Right	452
Do.[3]	51	291.2	200	12.3	5.18	1.50	do.	Left	477
Do.[3]	52	431.1	1,000	18.4	5.64	3.26	Kite No. 1	Right	1,481
Do.[3]	53	440.6	1,000	18.7	5.49	2.85	do.	Left	1,488
Do.[3]	54	444.8	2,000	38.0	10.54	3.46	do.	Right	1,536
Do.[3]	55	321.7	1,500	28.4	10.96	3.89	do.	Left	1,532
June 20[3]	56	330.9	500	27.3	10.55	5.08	Paper No. 1	Right	516
Do.[3]	57	368.7	600	30.5	10.62	5.22	do.	Left	552
Do.[3]	58	311.7	500	25.8	10.69	5.49	Al. cups	Right	540
Do.[3]	59	405.1	700	34.4	10.89	5.33	do.	Left	571
Do.[3]	60	298.1	900	49.3	20.14	4.82	do.	Right	540
Do.[3]	61	344.2	1,100	56.5	20.05	5.23	do.	Left	574
Do.[3]	62	223.8	700	37.2	20.43	5.94	do.	Right	552
Do.[3]	63	246.8	800	39.9	19.86	6.00	do.	Left	588
Do.	64	489.6	1,800	97.8	24.51	5.54	do.	Right	540
Do.	65	368.6	1,300	63.9	21.35	6.76	do.	Left	595
Do.	66	345.6	3,500	64.6	22.92	6.62	Kite No. 1	do.	1,591
Do.	67	361.4	3,500	65.8	22.35	7.61	do.	Right	1,560
Do.	68	270.0	3,500	67.3	30.35	7.29	do.	do.	1,538
Do.	69	323.9	5,000	90.2	33.95	8.38	do.	Left	1,637
Do.	70	332.7	1,800	84.8	31.30	8.73	Al. cups	do.	622
Do.	71	376.1	1,900	96.1	31.39	9.48	do.	Right	579
Do.	72	380.4	2,300	118.9	37.91	7.52	do.	do.	574
Do.	73	363.2	2,700	128.0	42.55	6.57	do.	Left	629
Do.	74	295.1	5,500	101.9	41.71	6.54	Kite No. 1	do.	1,609
Do.	75	323.6	6,000	113.6	42.85	11.05	do.	Right	1,558
June 26	76	356.8	1,200	67.1	22.80	4.51	Al. cups	do.	531
Do.	77	402.2	1,900	102.9	30.94	5.44	do.	do.	550
Do.	78	350.3	2,200	116.0	39.94	5.58	do.	do.	569
Do.	79	358.6	2,700	141.3	47.38	3.89	do.	do.	572
Do.	80	163.3	1,300	66.1	48.75	5.91	do.	do.	588
Do.[4]	81	189.3	800	40.7	25.88	2.96	do.	Left	588
Do.	82	357.0	1,200	62.8	21.24	3.36	do.	do.	570
Do.	83	357.5	1,700	82.0	27.67	4.05	do.	do.	619
Do.	84	364.0	2,400	118.8	39.29	4.25	do.	do.	604
Do.	85	352.9	2,900	138.3	47.35	7.77	do.	do.	625
Do.	86	329.0	3,000	142.3	52.06	5.84	do.	do.	631
Do.	87	315.5	3,000	58.3	22.26	2.90	Kite No. 1	Right	1,538
Do.	88	348.3	4,500	86.3	29.90	4.56	do.	do.	1,555
Do.	89	365.0	6,500	124.2	40.99	5.15	do.	do.	1,564
Do.	90	386.9	8,000	153.3	47.60	3.37	do.	do.	1,564
Do.	91	386.5	9,000	172.0	53.45	3.39	do.	do.	1,568
Do.	92	320.0	3,000	56.6	21.40	3.90	do.	Left	1,577
Do.	93	366.6	5,000	93.4	30.80	5.26	do.	do.	1,594
Do.	94	353.9	6,500	120.5	41.05	5.53	do.	do.	1,611
Do.	95	350.3	7,500	140.6	48.26	4.94	do.	do.	1,597
Do.	96	357.4	8,000	148.2	49.85	4.19	do.	do.	1,616
July 10	97	288.9	2,500	49.2	21.05	7.06	do.	Right	1,480

TABLE 2.—*Anemometer tests*—Continued.

Date.	No. of experiment.	t.	u.	N.	R.	W.	Instrument.	Direction.	U.
1899.									
July 10	98	348.5	4,500	87.2	30.17	4.07	Kite No. 1	Right	1,541
Do.	99	363.5	6,500	125.7	41.62	4.29	do.	do.	1,547
Do.	100	290.0	6,500	126.0	52.15	1.13	do.	do.	1,547
Do.	101	392.3	3,000	57.4	17.66	2.72	do.	Left	1,559
Do.	102	369.9	3,500	65.0	21.25	3.62	do.	do.	1,603
Do.	103	346.6	4,500	84.4	29.28	2.68	do.	do.	1,596
Do.	104	344.8	6,500	122.5	42.79	1.66	do.	do.	1,586
Do.	105	389.5	9,000	166.8	51.43	2.71	do.	do.	1,617
Do.[5]	106	356.5	3,000	56.7	19.33	3.96	do.	do.	1,567
Do.[5]	107	376.1	5,000	94.5	30.19	2.24	do.	do.	1,585
Do.[5]	108	354.0	6,500	120.9	41.08	3.95	do.	do.	1,609
Do.[5]	109	446.6	10,000	184.7	49.74	4.61	do.	do.	1,621
Do.[6]	110	382.1	3,500	61.8	19.80	5.50	do.	do.	1,665
Do.[6]	111	370.0	5,500	94.4	31.02	6.99	do.	do.	1,725
Do.[6]	112	366.4	6,000	122.1	40.17	5.44	do.	do.	1,468
		159.6	3,000	52.2	39.44	5.51	do.	do.	1,716
		206.8	3,000	69.9	40.74	5.38	do.	do.	[7]1,282
Do.[6]	113	376.0	9,000	150.3	48.08	4.54	do.	do.	1,792
		281.4	6,500	111.6	47.68	4.13	do.	do.	1,744
Do.[5]	114	410.6	3,500	68.1	20.17	4.62	do.	Right	1,521
Do.[5]	115	381.7	5,000	95.7	30.20	3.72	do.	do.	1,562
Do.[5]	116	235.8	3,500	67.4	34.45	4.47	do.	do.	1,551
		361.4	6,000	116.1	38.61	3.11	do.	do.	1,548
Do.[5]	117	356.7	7,500	142.6	48.10	4.48	do.	do.	1,574
Do.[6]	118	376.9	3,500	64.3	20.73	4 58	do.	do.	1,613

[1] Wind measured by anemometer on vertical spindle of whirling machine.
[2] Wind measured by anemometer on pole located to windward of whirler on and after May 26, 1899,
[3] By hand Anemometer registration every fifty revolutions.
[4] Contact defective.
[5] Anemometer tilted forward 20°.
[6] Anemometer tilted backward 20°.
[7] Spindle bearing unscrewed.

Explanation of Table 2.—The effective duration of a test is given in seconds in the column headed t; u is the number of revolutions of the anemometer in t seconds; N is the number of revolutions of the whirler in same time; W is the mean velocity of the wind during the experiment; R is the mean resultant velocity of the artificial wind experienced by the anemometer being tested; U is the number of revolutions made by the anemometer per mile of resultant wind movement.

The following equations apply:

$$V = \text{Velocity at end of arm} = 120 \frac{N}{t}$$

$$R = \text{Resultant wind} = V + \frac{W^2}{4V}$$

U = Number of revolutions of anemometer per mile of wind.

$$U = \frac{3600\,u}{R\,t}$$

The dimensions of the several "sets of cups" are as follows:

	Standard, aluminum.	Kite No. 1.	Kite No. 2.	Paper No. 1.	Paper No. 2.
Mean diameter of cups, inches	4.07	1.22	1.22	4.11	4.14
Length of arms to cup centers, inches	6.65	1.96	1.96	6.68	6.65
Diameter of arms, inches	0.11	0.03	0.03	0.10	0.14
Weight, ounces	9.56	0.33	0.31	1.27	1.72
Moment of inertia, grams, c^2	51330	....	....	....	7788

The moments of inertia were measured in a former investigation, made in 1894, using for this purpose the torsional pendulum illustrated in fig. 7. By noting the time of oscillation of the pendulum, when loaded with the cups, as shown, the moment of inertia is easily computed by comparison with the times of oscillation when loaded with a weight of some simple form of known moment of inertia, such as the cylinder c. It was convenient, also, to swing long cylindrical rods whose moment of inertia could easily be computed. In this case the rods were placed in the stirrup holding the cups, as shown in the figure. The torsional pendulum shown was too stiff to use for the small kite anemometer and its moment of inertia was not ascertained.

GENERAL RESULTS.

The tests of the paper cups[4] were limited to low velocities, as these were used only in measuring natural wind. The following mean values of U were found:

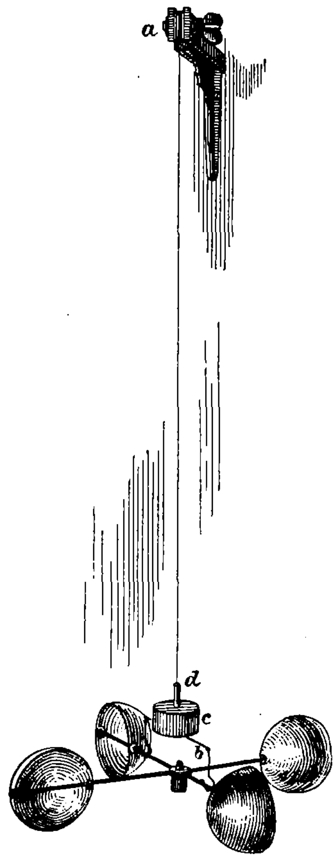

FIG. 7.

Paper No. 1.			Paper No. 2.			U deduced from 1888 experiments.
Number of tests.	Velocity, in miles per hour.	U.	Number of tests.	Velocity, in miles per hour.	U.	
4	5.45	486	4	5.44	485	494
4	10.00	556	2	10.20	560	525

The above results embrace in all only 14 tests, and yet the agreement may be regarded as very satisfactory. The value of U, given in the last column deduced from the experiments of 1888, applies strictly to an anemometer of greater moment of inertia than the paper cups, and according to theory should be slightly higher for the same conditions.

[4] *Construction of paper cups.*—It may be interesting to know how the paper cups were made. A hemispherical metal cup, such as used on the standard anemometers served as a model or mould over which the paper cup was constructed. A strip of stiff, strong paper is cut out of sufficient length to encircle the mouth of the cup allowing a slight lap. One edge is subdivided into twenty equal parts, each of which is made the base of a gore or triangle with curved sides; that is, these gores correspond exactly to the spherical triangles on a globe between the meridians of longitude and with their bases at the equator. The superfluous paper between the gores is carefully cut away, except close to the base where all the gores join together. The strip of paper thus prepared can be fitted very closely to the metal form, and the edges of the gores united by gluing a narrow strip of thin linen paper over the seams. The apex or pole of the gores should be strengthened by a small disk of strong paper. A narrow girdle should also be fitted and glued across the gores at about 45° of latitude. The cups were mounted on slender wooden arms, to which they were secured by wax, one or two coats of shellac varnish were applied to keep out moisture. Carefully made cups of this character will run for some time in the ordinary gusty winds averaging from 20 to 25 miles per hour.

The mean results of the tests of the standard aluminum cup anemometer and of the No. 1 kite anemometer are given in the following table, together with the values of U deduced from the experimental work of 1888.

Standard aluminum cup anemometers.					Kite anemometer No. 1.		
Number of tests.	Velocity.	U.	U, 1888 experiments.	Difference.	Number of tests.	Velocity.	U.
....	....	......	....	....	2	5.56	1,484
4	10.98	581	530	−51	6	10.88	1,569
8	21.30	561	572	+11	11	21.25	1,563
8	30.25	584	593	+ 9	9	31.17	1,575
12	40.08	600	612	+12	18	40.85	1,584
4	48.88	604	626	+22	12	49.52	1,587

From the column of differences it appears that the new results show a slightly lower rate of speed of the anemometer in a given wind than formerly deduced. It is worth noting, however, that the sum of the plus and minus differences just balance each other, but we regard this as no more than a coincidence. Nevertheless, the results based on the greater number of observations show a very satisfactory agreement, the discrepancy being less than 2 per cent. We may therefore conclude that these tests in the open air afford a most substantial confirmation of the general accuracy of the older investigations which were made by a method that we now regard as less direct and trustworthy.

It is regretted that the crude and improvised installation of the apparatus and the insufficient power of the small engine available restricted the investigation in several ways and limited the speed attainable to velocities below such as frequently occur in regular station observations. The great irregularity of results unavoidably incident to this method of experimentation and the limited number of tests at each velocity thus far obtained, do not, in the writers opinion, warrant any further refinement of discussion than that given above.

An effort was made to ascertain the effect of tilting the axis of the anemometer forward and backward at moderate angles and the experiments noted in Table 2 were made. The results were, in some cases, vitiated by faulty action and were not on the whole satisfactory. Time was not available to continue these studies, but I think it is demonstrated that the error in the indications of an anemometer attached to a kite is not of a serious character, even when the axis of the instrument deviates continuously as much as 20° from the vertical. In good kite work the deviation can easily be reduced much below this.

In conclusion, it is noticed that the value of U for the kite anemometer for velocities from 10 to 50 miles per hour is almost constant, the extreme variation being only about 1.5 per cent. This again confirms a conclusion to this same effect reached in 1888, namely, that anemometers whose cups are large, as compared with the length of arms, run at a speed bearing a more nearly constant ratio to that of the wind than do anemometers with relatively longer arms.

TWO THUNDERSTORMS AT THE ROYAL ALFRED OBSERVATORY, MAURITIUS.

By T. F. CLAXTON, Director, dated February 12, 1900.

The reproductions of the Mauritius meteorgrams (Chart XI) are more eloquent than any account of the two thunderstorms which occurred at the Royal Alfred Observatory on January 29 and 30, 1900; though a few words are necessary for the clear interpretation of the registers.